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Climate adaptive building shells: State-of-the-art and future challenges

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ABSTRACT

Successful building design is becoming an increasingly complex task, due to a growing demand to satisfy more ambitious environmental, societal and economical performance requirements. The application of climate adaptive building shells (CABS) has recently been put forward as a promising alternative within this strive for higher levels of sustainability in the built environment. Compared to conventional façades, CABS offer potential opportunities for energy savings as well improvement of indoor environmental quality. By combining the complementary beneficial aspects of both active and passive building technologies into the building envelope, CABS can draw upon the concepts of adaptability, multi-ability and evolvability. The aim of this paper is to present a comprehensive review of research, design and development efforts in the field of CABS. Based on a structured literature review, a classification of 44 CABS is made to place the variety of concepts in context with each other, and concurrent developments. In doing so, the overall motivations, enabling technologies, and characteristic features that have contributed to the development of CABS are highlighted. Despite the positive perspectives, it was found that the concept of CABS cannot yet be considered mature. Future research needs and further challenges to be resolved are therefore identified as well.

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1. Introduction

Last decades, the design of low-energy buildings has diverged into two alternative directions: active technologies and passive design strategies [1–3]. The first approach aims at enhancing the level of sustainability in the built environment via the introduction of innovative technical devices. Such devices are used for decentralized generation and supply of energy from renewables, or for conversion of resources at higher overall efficiencies [4]. The term passive on the other hand refers to buildings where the design of construction and shape of the building itself, as opposed to its servicing, play major roles in capturing, storing and distributing wind and solar energy, normally with the aim of displacing fossil fuels for space conditioning and lighting [5–7].

Apart from the energy conservation agenda [8], the building sector simultaneously gets confronted with an increasing need to develop spaces that are as healthy, productive and pleasant as possible, and all that in a cost-effective way. Seen in the light of these ongoing developments, it is debatable whether either the active, or the passive track independently can fulfill these integrated goals.

In the challenge of harmonizing energy performance within the wider scope of overall building performance, it may be worthwhile to reconsider the role of the building's enclosure. Most of the conventional building shells are designed with a central focus on providing shelter and protection. This is often accomplished by making the indoor environment to a large extent insensitive to its surroundings. The inconvenient consequence is that considerable mechanical and electrical systems are to be installed for providing heating, ventilation, air-conditioning (HVAC) and artificial lighting, in order to satisfy comfort requirements at the expense of energy consumption and the use of other natural resources.

Building shells are located at the boundary between inside and outside, and are therefore subject to a range of variable conditions. Meteorological conditions change throughout the day and the year, and this also applies to occupancy and comfort wishes. Conventional building shells, typically have static properties, and no ability to behave in response to these changes. Making the shift to climate adaptive building shells (CABS) offers opportunities to take advantage of the variability that is available, and therefore would allow for a transformation from ‘manufactured’ to ‘mediated’ indoor climates [9]. By embodying the paradox of combining the complementary aspects of passive design with active technology, CABS offer a high potential to reduce the energy demand for lighting and space conditioning. At the same time, also positive contributions to indoor air quality and thermal and visual comfort levels can be expected.

Architecture has not always considered the ambient environment an adversarial constraint in the design process. Many cases of bioclimatic and ancient vernacular architecture show good examples of how building design can deliberately take advantage of available conditions in the exterior environment [10]. Also the prospect for adaptive rather than static façades is already being pursued for some time. Back in 1981, Mike Davies speculated on the potential of CABS with his visionary concept of a ‘polyvalent wall’ [11]. For many years however, technological restrictions have prevented CABS from being considered a viable alternative [12,13]. By taking advantage of rapid advances in material sciences, contemporary professionals now have plenty of options available for making façades adaptive [14–20]. A parallel trend of dropping prices for hardware, sensors and actuators make that CABS now also become more attractive from an economical point of view [21,22]. The “development, application and implementation of responsive building elements” is a necessary step towards further energy efficiency improvements in the built environment, according to a recently completed project of the International Energy Agency—Energy Conservation in Buildings and Community Systems Programme (IEA-ECBCS) [23].

Discourse on the topic of CABS is thus far mainly centered around iconic examples, including the diaphragm shutters of Jean Nouvel's Arab World Institute in Paris (Fig. 1), and Rolf Disch's rotating Heliotrop in Freiburg (Fig. 2). Often, these buildings are quoted as impetus for renewed interest in CABS. A comprehensive overview that summarizes research, design and development efforts is not yet available in literature.

The aim of this paper is to provide a review and analysis of CABS that goes beyond the classic examples, by exploring the current state of the field in terms of (i) built examples, (ii) subsystems and components, (iii) full-scale prototypes and (iv) reduced-scale prototypes. Section 2 starts with establishing a proper definition of CABS to set the boundaries of the present work. By borrowing terminology from the field of flexible systems engineering, the need for more adaptability in the built environment is then advocated in Section 3. This is followed by providing an overview of the state-of-the-art in the field to point out some particularities of individual examples, but mainly to extract the overall trends and observations of CABS in general. Section 4 discusses the main findings of the literature review along five themes: (i) sources of inspiration, (ii) relevant physics, (iii) time-scales, (iv) scales of adaptation and (v) control types. The results are then synthesized in the form of a table. Section 5 concludes the article with setting a research agenda, by indicating some of the barriers and impediments that need to be overcome before the concept of CABS can become a success on a larger scale.

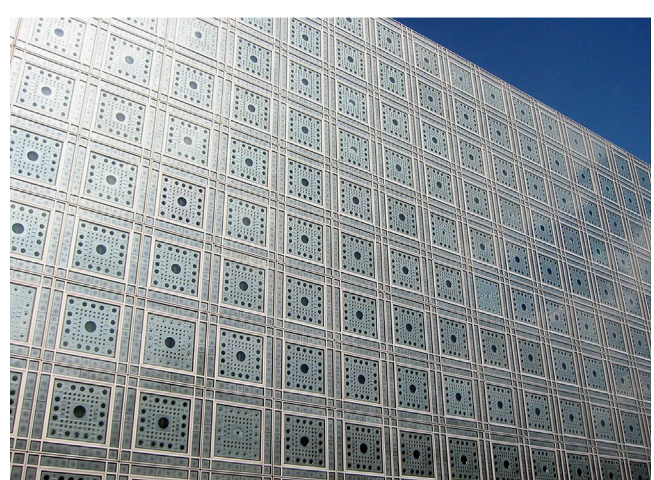


Fig. 1. Arab World Institute, Paris.



Fig. 2. Heliotrop, Freiburg.

Although there is a need for analysis of typical CABS projects, it is not within the scope of this paper to present case study descriptions and technical details of specific projects. Such detailed analyses would require data that is not commonly available, in particular, construction details and information about CABS' monitored operational performance and post occupancy evaluations are lacking in literature. For an overview of typical projects, the reader is referred to the database in Ref. [24], which has been continuously updated and covers at the moment more than two hundred examples of buildings with CABS.

2. Defining CABS

CABS is only one designation for a concept that has been described by a multitude of different terms. In this context, both practitioners and researchers favour the use of several variations on the term 'adaptive', including: active [25], advanced [26], dynamic [27], intelligent [13,28,29], interactive [21], kinetic [30], responsive [31], smart [32], switchable [33], etc. Although all these expressions have a somewhat different meaning, they are often used interchangeably and in an ad hoc manner. In order to avoid ambiguity, we adopt the term CABS, and define it as follows:

> A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance.

The building shell is interpreted here as those construction elements that form the division between inside and outside air. This includes both the opaque and transparent wall elements as well as the roof. Adaptive behavior in internal partitions, floors and foundation is not taken into account.

CABS differentiate from the prevailing trend in façade design that is being characterized by the term 'innovation by addition' [34]. In common practice, the design challenge is decomposed in a series of subproblems related to appearance, structural support and transfer of heat, light, sound, fresh air and moisture [35]. Typically, this sequential approach also tends to result in a subdivision of only partial solutions that often takes the form of a sequence of functional layers. The recent interest in application of double skin façades [36] may be seen as the sophisticated exponent of this established practice. The concept of CABS however intends to go a step further, by reconciling the multiple competitive performance aspects in a more holistic way. The presented definition of CABS therefore puts special emphasis on the performative aspects of the building shell for support of indoor environmental quality. By embracing this definition, a number of building shell technologies that do qualify as e.g. active, advanced or interactive fall outside the scope of the present work. A typical example is formed by the group of media façades [37,38]. These façades do introduce dynamic aspects to the building, but do not have the means to effectively influence perceived indoor climate. Also building integrated photovoltaics (BIPV), and complex, but static daylighting systems [39,40], are not included in this review, as this technology is not capable of actively responding to variable conditions.

3. The need for CABS

The practical application of buildings with CABS has thus far remained limited, despite of rising appreciation for the conceptual qualities. Those examples that have been built are mainly restricted to either small-scale experimental projects or the high-profile, high-budget projects. The added value of adaptive rather than static system designs is however widely valued in many other engineering disciplines. Such developments came together with a rich body of terminology for describing the various aspects of changeability. In this section, these constructs are transferred to the domain of buildings and architecture, for (i) illustration of potential application areas of CABS, and (ii) justification of further research efforts.

3.1. *Reconciling robustness and flexibility*

The terms robustness and flexibility both refer to an ability for handling change. The way a system responds to changing conditions marks an important distinction between the two. In interpreting flexibility in relation to CABS, we follow the work by Saleh et al. [41] that robustness and flexibility are relative concepts. Any attempt to describe flexibility should therefore also clarify the relationship with robustness and the system's fixed counterpart [41,42].

A fixed, static, or nonflexible system has no inbuilt capability to respond to changing conditions. Such a system may therefore not offer satisfactory performance if the operating environment or system requirements change over time. In fixed systems, performance degradation of this type can be overcome by introducing robustness, through e.g. oversizing, partitioning, redundancy and scalability [43]. Robustness as a system property aims at reducing the negative consequences due to external changes, but does not intend to eliminate the causes of it. In accommodating fixed systems to perform well under a wider range of conditions, robustness is usually achieved at the cost of a decrease in performance under nominal conditions. In addition, robust static designs typically have difficulties to cope with unexpected conditions.

Flexible systems on the other hand can be defined as systems designed to maintain a high level of performance through real-time changes in configuration when operating conditions or functional requirements change in a predictable or unpredictable way [44]. More intuitively: flexible systems make transitions over time [45], to meet new circumstances and cope with uncertainty, and thus imply an ease of modification and absence of irreversible or rigid components [46]. Whereas robust designs try to neutralize the impacts of external perturbations, flexible designs do the opposite by intentionally exploiting the changes in their environment. Through anticipation and reaction in the face of change, flexible systems are more likely to maintain performance robustness than a robust static system design.

In the end, this notion has been the underlying motive in the search for means of making the built environment more responsive and dynamic, thus flexible [28]. In relation to the building shell, the ways of flexibility to support performance during a building's lifecycle can be illustrated by using three different properties: adaptability, multi-ability and evolvability. Sections 3.2–3.4 deal with these properties in more detail.

3.2. Adaptability

Ferguson et al. [47] define adaptability as the ability of a system to deliver intended functionality considering multiple criteria under variable conditions through the design variables changing their physical values over time. Building shells having this attribute can seize the opportunity to deliberately act in response to changes in ambient conditions. Doing this offers a potential for energy savings compared to conventional buildings because the valuable energy resources in our environment can be actively exploited, but only at times when these effects are deemed favourable. CABS can thus act as climate mediator [9], negotiating between comfort needs and what is available in the ambient environment. With CABS, façades no longer have to be a compromise solution for the whole year. Moreover, it gives opportunities to adjust to the individual user, rather than a best average for all, as usually recommended in standards. In addition to the immediate effect, CABS' adaptability also helps in achieving gains through smart utilization of building constructions' thermal storage capacity. The dual effects of shifting peak demands can help in mitigating comfort problems, and also limit redundancy in installed heating and cooling capacity [48].

3.3. Multi-ability

The concept of multi-ability originates from the existence of non-simultaneous performance requirements, or the need to fulfil new roles over time. The 'balcony that can be folded' [49] is an illustrative example of a CABS that features multi-ability: depending on ambient conditions and users' preference, it changes function from window to a balcony-on-demand [50]. Multi-ability differs from adaptability in the sense that multiple objectives can be fulfilled consecutively, not concurrently [47]. Unlike conventional systems, designed to satisfy a single set of conditions, it allows for addressing change via a plurality of optimized states. By doing this, multi-ability promotes more efficient use of resources, which adds to the list of benefits already mentioned in the previous paragraph. A second application of multi-ability is the potential for spatial versatility. At the same moment in time, the properties of the building envelope can be different for various positions of the building shell. In this way, different faces of the building shell can independently react to the ambient conditions or to distinct comfort preferences requested by individual users in separate zones.

3.4. Evolvability

Where adaptability and multi-ability mainly deal with short-term variations, evolvability is a property of flexibility that handles changes over a longer time-horizon [51]. Even more than uncertainty in everyday operation, future building requirements and boundary conditions are highly unpredictable, or cannot even be known in the design stage [52]. Building shells that can evolve over time are a means of extracting value from the uncertainty of these unforeseen events. Evolvability is considered more a positive side-effect, rather than primary design objective; the ability to keep options open preserves opportunities to react to changes in future. Concerning the built environment, evolvability, or sometimes called survivability [53], can be employed to deal with changing conditions coming from the outside (e.g. climate change, changing urban environment, wearing of the façade) or from the inside (e.g. organizational function changes of the building, new space layout). In all these cases, application of CABS increases the chances that the building can continue operation as intended, without suffering from the potential negative impacts of unforeseen future conditions [54].

4. CABS state-of-the-art and beyond

Progress in the field of CABS is dispersed and characterized by fragmented developments based on advances in material sciences and the imaginative capacity in design teams. In order to explore CABS in its full diversity, a structured literature survey has been conducted. For this purpose, numerous pairs of search terms were used. The first keyword was selected from the variations on the term adaptive as mentioned in Section 2, while the second keyword was always picked from one of the following words: architecture, building, cladding, enclosure, envelope, exterior, façade, glazing, roof, shell, skin, wall or window. The number of existing products, built examples, design proposals and research prototypes that appeared in books, patent applications, and journal- and conference papers is relatively limited. Moreover, extensive review papers have not yet been published. Given that progress in CABS frequently arises on a casual basis as outcome of creative processes, the results are often proprietary and far from always published in scholarly literature. The scope of this review was therefore not limited to scientific articles only, but also included e.g. architecture and design magazines, weblogs, video portals and websites of commercial organizations. Eventually, over one hundred CABS concepts were found [24], and classified according to their characteristic properties [55]. The overview and classification presented in this paper only includes the concepts that are supported with information on their working principles and are citable. The classification aims to place the variety of CABS in context with each other and thereby reveals general trends and patterns, and discovers factors that have been critical to the early applications of CABS. The outcomes further also identify possible barriers and directions for future research, to be discussed in Section 5. This section reports on the main outcomes of the literature review along five themes: (i) sources of inspiration, (ii) relevant physics, (iii) time-scales, (iv) scale of adaptation and (v) control types, and is then followed by a comprehensive summary.

4.1. Sources of inspiration

Apart from mere curiosity, a welter of sources served as input in the search for adaptive instead of static building shells. Nature is commended as one of the most prominent inspiration sources for CABS. Adaptability is pervasive in nature, and efforts in biomimicry

to convey nature's time-tested ideas to the context of buildings are rewarding [56,57]. The way people sweat, shiver and adjust clothes has been used by many as a metaphor to conceive the building skin as a living membrane [28,58]. Likewise, several CABS concepts imitate tropism: plants' directional growth or rotation in the direction of certain environmental triggers. Both phototropism (i.e. changing in response to light) and heliotropism (i.e. changing in response to the sun) have been transformed effectively into CABS concepts, enabling timely collection and rejection of solar energy [59,60].

Examples of CABS mainly originate in settings were creativity is extra valued, and the emphasis on practical aspects and costs is relaxed. More than in our actual building stock, traces of CABS are found as output of academic endeavors [61], in cultural exhibitions [62], and as recurring elements in design competitions like the Solar Decathlon [63,64].

One of the other commonalities of CABS is a predilection for innovative materials, sometimes inspired by other disciplines like display technology [65] and the printing industry [66]. Following the fundamental research community, nanotechnology is now also receiving more and more attention among building designers. At present, most products on the market come as coatings that make surfaces e.g. anti-bacterial, anti-graffiti, fire-proof, scratch-proof, self-cleaning or abrasion-resistant [17]. In the long run, nanotechnology holds the premise to build materials bottom-up [67], and in doing so provides the opportunity to create materials with the desired adaptive properties.

4.2. Relevant physics

Building shells form the division between the ambient environment and indoor zones of a building, and therefore function as the interface where several physical interactions take place. Every CABS influences this multi-physical behavior in its own characteristic way, by for example blocking, filtering, converting, collecting, storing or passing through the various energy fields. In order to characterize the differences and similarities in CABS, four domains are distinguished, as defined in Table 1. In fact, most CABS influence performance in more than one domain. The interdependencies are visualized via the four-ellipse Venn diagram in Fig. 3. The four domains, and all possible multi-physical overlaps together, result in a number of fifteen different possible combinations to represent the relevant physical interactions of a CABS concept. Some other possible domains, such as moisture and sound, were not included because no example was found in literature.

4.3. Time-scales

As discussed before, buildings are subject to various environmental impacts. All these influences typically occur at a characteristic temporal resolution, ranging from the order of sub-seconds to impacts that are only perceptible during the building's whole lifetime. The following list provides an overview of the most dominant time-scales in relation to CABS.

Seconds These short-term fluctuations typically are stochastic in nature. The swift variations in wind speed and direction for example, enable movement in wind pressure based façade systems [68,69]. CABS with sensors that behave in response to people's direct vicinity are also capable of changing their configuration on this short time-horizon.

Minutes Cloud cover and daylight availability have a characteristic time constant in the order of minutes. That is the reason why all CABS that aim to optimize daylight utilization and solar shading for reducing energy demand and increasing visual comfort are required to alter their degree of transparency at a rate of change in the order of minutes. As the bulk of CABS concepts is designed to adapt in response to availability of solar radiation, they consequently fit into this category.

Hours Angular movement of the sun through the sky is a continuous process. However, CABS that track the path of the sun typically adjust in the order of hours [64]. Fluctuations in air temperature, both internal and external, can appropriately be discretized in hourly values as well. CABS that directly adapt in response to temperature stimuli [70] are consequently also classified in this category.

Diurnal Presence of occupants in buildings normally follows diurnal patterns. In addition, these day-night cycles are also noticeable in meteorological boundary conditions like ambient air temperature and availability of solar radiation. Some CABS are specifically designed to take advantage of this fixed 24 h pattern. Examples are the adaptable thermal storage in solar barrel wall [71], and the nocturnal release of thermal energy via roof ponds with moveable insulation [72].

Seasons Adapting to variability in conditions across the seasons is arguably the most elegant application area of CABS. Winter, spring, summer and autumn all impose widely different boundary conditions, particularly in medium and high latitudes. Buildings that can adapt to these changes are expected to provide substantial performance benefits. An illustrative example of seasonal CABS are bi-directional thermal diodes [73]. These wall constructions

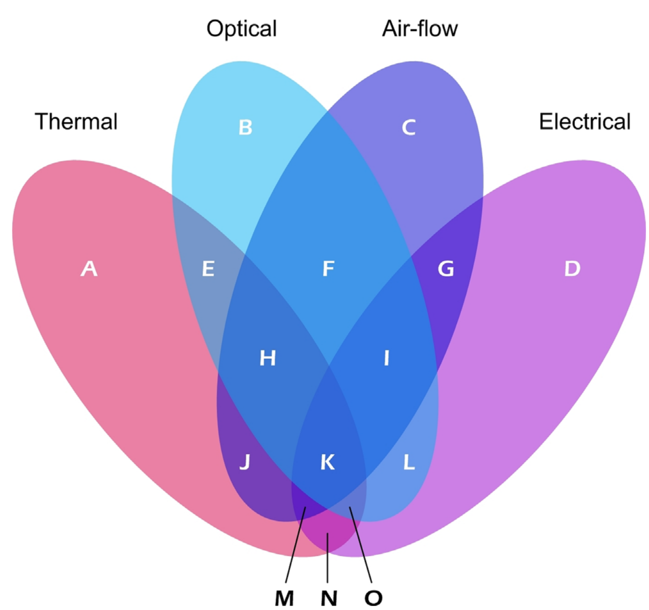


Fig. 3. Classification of relevant physics: each CABS can be characterized by one of the fifteen areas in the figure.

Table 1
Description of the physical domains.

Thermal	Adaptation causes changes in the energy balance of the building via conduction, convection, radiation and storage of thermal energy
Optical	The adaptive behavior influences occupants' visual perception via changes in the transparent surfaces of the building shell
Air-flow	A flow of air across the boundary of the façade is present, and adaptive behavior is influenced by the direction and speed of the wind
Electrical	Building-integrated energy generation takes place on the façade level, or electricity consumption is an essential part of the adaptation mechanism

can either promote or suppress heat transfer across its boundary, depending on thermal load of the zone and temperature difference with outside.

4.4. Scales of adaptation

The mechanisms that foster adaptation in CABS can be distinguished in two classes. The adaptive behaviour is either based on a change in properties or behaviour at the macro scale, or at the micro scale; although combinations are also possible. The distinction between both mechanisms is raised by the spatial resolution at which adaptive actions take place, as described below in more detail.

4.4.1. Macro scale

The first type of adaptability in building shells is often also referred to as 'kinetic envelopes', which implies that a certain kind of observable motion is present. Adaptation on the macro scale usually results in changes in the building shell's configuration via moving parts. This can be through (i) supplemented components, external to the building shell (e.g. Burke Brise Soleil, Milwaukee art museum [74]), (ii) subsystems of the building shell itself (e.g. Eco-spirit [75]), (iii) movement of the entire façade (e.g. Museum of Paper Art [76]), as well as (iv) the building as a whole (e.g. Dubai Rotating Tower [77]). The types of motion that can be observed vary widely, and are typically described by one of the following gerunds: folding, sliding, expanding, creasing, hinging, rolling, inflating, fanning, rotating, curling, etc. Apart from CABS with dynamic mechanical components, there has also been interest in façade systems where movement is attained by transportation of fluids. Different types of flowing media in façade elements have been explored, including flow of air [78], foam bubbles [79], polystyrene beads [80], phase change materials [81], and water in transparent [82,83], as well as opaque constructions [84,85].

4.4.2. Micro scale

In the other type of CABS, changes directly affect the internal structure of a material. Here, adaptability is either manifested via changes in thermophysical [86,87] or opaque optical properties [88,89], or through the exchange of energy from one form to another [25,90]. The majority of micro scale CABS however, is concerned with the light transmitting properties of materials. These *smart windows* have the ability to modulate levels of incoming daylight and solar energy by adjusting their optical properties. After more than three decades of work on switchable glazing, numerous working mechanisms have been licensed, and are at present being sold as commercial products [91]. Switchable windows are traditionally subdivided into three groups according to type of activation mechanism, i.e. responding to surface temperature [92], incident radiation [93], or external control signals [33]. By taking advantage of continual developments, a next generation climate adaptive windows is now about to enter the field, having e.g. light redirecting properties [94], enhanced spectral selectivity [95,96], better opportunities for mass production [97], or the ability to produce electricity for its own operation [65,98].

4.5. Control types

Effective control is a key element for successful operation of CABS. Two different control types are distinguished in the analysis: extrinsic and intrinsic control. Specific advantages and disadvantages of both types are discussed below.

4.5.1. Extrinsic control

The distinguishing quality of CABS with extrinsic control is the ability to take advantage of feedback. Feedback implies that the effects of the current configuration (action) can be compared to the desired state (set-point), and if necessary the behavior of the building shell can be adjusted actively. The structure of extrinsic controlled CABS consists of three basic elements: sensors, processors and actuators [99]. The combination of these three, together with control logic to close the loop, make that adaptive behavior is able to change intent into action at two different levels:

1 Distributed, via embedded computation in local processors, or
2 Centralized, driven by a supervisory control unit to achieve global target values.

4.5.2. Intrinsic control

CABS with intrinsic control are characterized by the fact that the adaptive capacity is an inherent feature of the subsystems comprising the building shell. CABS of this type are self-adjusting since the adaptive behavior is automatically triggered by environmental stimuli like: temperature, relative humidity, precipitation, wind speed and direction, solar radiation, cloud cover or CO_2-level. This type of autonomous control is sometimes also called 'direct control' [30] because environmental impacts are directly transformed into actions without external decision making component. One could also state that the elements in intrinsic CABS concepts are at the same time both sensor and actuator. In practical applications, this type of activation is often attained by using a special class of materials with advanced functionality, also termed smart materials [14,15,19].

An advantage of intrinsic CABS compared to CABS with extrinsic control is that these types of systems can immediately change their configuration without expending any fuel or electricity to facilitate the state transition. In addition, the subtlety of the technology is a main asset: the number of components is limited since no hardware for control units, processors or wires are necessary. The adaptive features in intrinsic CABS are typically designed by tuning material properties or other system variables to a certain range of expected conditions. As soon as real-occurring disturbances deviate from design conditions, the intended performance is no longer guaranteed. A main drawback of CABS with intrinsic control therefore is the fact that the systems can only adapt in response to those variations that were expected in the design stage. The impossibility for manual intervention, and integration in centralized high level control systems are regarded as additional disadvantages.

4.6. CABS overview

The present state-of-the-art overview features a large diversity in concepts and also shows a growing interest in climate adaptive architecture. Table 2 provides a comprehensive overview of the findings by summarizing the characteristic features of 44 CABS concepts. The table subdivides CABS in four groups of eleven concepts. The first group consists of buildings that are actually being occupied, or will be in the near future. The group 'subsystems and components' contains CABS that have been used in real buildings, but can be applied universally rather than being attributed to one particular building. Groups three and four consist of CABS concepts that did not yet find their way to the market, but exist in the form of prototypes. Two types were distinguished here, where (i) the working mechanism is being demonstrated on the full-scale, or (ii) the prototype is being tested in a reduced-scale proof-of-concept phase. For each CABS concept the table

Table 2
Summary of state-of-the-art CABS concepts.

	Ref.	Relevant physics	Scale of adaptation		Control type		
			Micro	Macro	Intrinsic	Extrinsic	
Built examples							
Arab World Institute	–	E		X		X	Jean Nouvel, Paris, France 1988
Burke brise soleil	[74]	E		X		X	Santiago Calatrava, Milwaukee, Wisconsin, 2001
Dubai rotating tower	[77]	E		X		X	David Fischer, Dubai, UAE, in progress
EWE Arena	–	K		X		X	ASP Architekten, Oldenburg, Germany, 2005
Heliotrop	–	O		X		X	Rolf Disch, Freiburg, Germany, 1993
Media-TIC	[100]	E		X		X	Cloud9 Architects, Barcelona, Spain, 2011
Museum of paper art	[76]	H		X		X	Shigeru Ban, Shizuoka, Japan, 2002
Solar barrel wall	[71]	A		X		X	Steve Baer, Corrales, New Mexico, 1971
Sliding house	[101]	E		X		X	dRMM Architects, Suffolk, UK, 2008
ThyssenKrupp headquarters	[102]	E		X		X	Chaix & Morel / JSWD, Essen, Germany, 2010
Zollverein school	[84]	A		X		X	SANAA, Essen, Germany, 2007
Subsystems and components							
Allwetterdach	[103]	H		X		X	
Balcony that can be folded	[49]	H		X		X	
Beadwall	[80]	E		X		X	
Breathing wall	[68]	J	X			X	
Bubble insulation	[79]	E		X		X	
Electrically heated glass	[90]	O	X			X	
GLASSX®crystal	[104]	E	X		X		
Photochromic glazing	[93]	E	X		X		
Roof pond	[72]	A		X		X	
Swindow	[69]	H		X	X		
Thermochromic glazing	[92]	E	X		X		
Full scale prototypes							
Adaptive fritting	[62]	E		X		X	
Aegis Hyposurface	[105]	A		X		X	
Bi-directional thermal diode	[73]	A		X		X	
Black & white house	[64]	O		X		X	
Deployable external insulation	[70]	E		X	X		
Fluidized glass façade	[82]	E		X		X	
Living glass	[56]	H		X		X	
Lumenhaus	[61]	E		X		X	
SmartWrap	[66]	O	X		X		
SolVent	[78]	H		X		X	
Thermocollect	[106]	A		X		X	
Reduced scale prototypes							
Active building envelope (ABE)	[25]	O	X			X	
Eco-spirit	[75]	O		X		X	
Electroactive polymer window	[95]	E	X			X	
Flectofin®	[60]	E		X		X	
Microblind	[97]	E	X			X	
Micromirror	[94]	E	X			X	
PCM window	[81]	E		X		X	
Solar collectors with tunable transmission	[65]	O	X			X	
Super cilia skin	[107]	K		X	X		
Switchable insulation	[86]	A	X			X	
Thermochromic paint	[88]	A	X		X		

further contains three characteristics: relevant physics (Section 4.2), scale of adaptation (Section 4.4) and control type (Section 4.5).

From Table 2, we can observe that the relevant physical domains from Fig. 3 are relatively dispersed over the presented examples. The thermal domain is relevant in all CABS examples. This is a direct consequence of the fact that the building's thermal environment is constantly changing. Optical effects play a role in 35 instances. These are all cases where controlled daylighting is part of the climate adaptive strategy. Airflow needs to be considered in eight of the CABS in the overview. And finally, the electrical domain, mainly in the form of photovoltaics, is encountered in nine of the 44 adaptive building shells.

Both control type and scale of adaptation do show a strong tendency towards one of the two possible alternatives. Table 3 provides further insights in the respective distributions. We can observe that the majority of cases is of the extrinsic control type with adaptation on the macro scale. In practical settings, this prevailing trend is manifested via sensor networks that drive servomotors, pumps or fans as actuator. This way of adaptive behavior is chosen in all eleven occupied buildings with CABS, and is therefore considered as the most conservative solution. The future of CABS, now still existing in the form of prototypes, however signals the emerging trend towards market introduction of other, more innovative adaptive mechanisms.

Table 3
Distribution of control types and scales of adaptation.

	Micro scale	Macro scale
Intrinsic type	5	3
Extrinsic type	8	28

5. Concluding remarks

This paper brings together the present state of research, design and development in the area of CABS from various scientific disciplines and design practices. A definition for CABS was established, and after that the interest and further efforts were justified from a flexible systems engineering perspective. The projects under review in this paper suggest that widespread application of CABS holds the promise of becoming a profound contributor to satisfy our increasingly stricter energy performance targets, without being constrained by the need for concessions in terms of comfort. At the same time, our findings also identify valuable directions for future building projects and developments in CABS research. The relatively limited number of documented cases reveals that at this point CABS cannot be considered a mature concept. In particular, information about CABS' monitored operational performance and post occupancy evaluations is lacking in literature. This final section of the paper therefore identifies some of the most important barriers, and proposes valuable directions for future research that can help to unlock CABS' latent potential. We conclude the paper with a view on the future perspectives of CABS.

5.1. Design and decision support

CABS projects often involve innovative technologies, resulting in challenging projects with relatively high risks. Project developers tend to take conservative attitudes to adopt this type of new technology because the risks are associated with chances for disproportionate payback times due to higher investment, maintenance and/or failure costs. Taking a risk however also offers opportunities, but such high ambition levels need to be supported by well-informed design decisions. To allow CABS to move away from an abstract concept to become a feasible design alternative demands for tools that are capable of genuinely predicting operational performance in the building design stage [108]. In turn, this increases transparency about how performance benefits during operation might outweigh fist cost arguments, and helps to overcome the cautious attitude introduced by the 'anchoring' bias towards prescriptive and standard design solutions [109]. A complicating factor herein is that performance benefits of CABS are both cumulative and delayed. Because performance of CABS is very case specific and also depending on context, capturing it in universal rules or rating schemes is impracticable. In contrast, building performance simulation [110] is regarded a promising tool, although more developments are needed to fully meet the requirements. Both flexibility of features to model adaptive behavior, and integration of impacts from the various physical domains are open to further development [111]. In parallel, it would be interesting to investigate opportunities to enrich capabilities of building performance simulation tools, by taking benefit from recent progress in those design methods, especially developed to aid in the design of adaptive systems [51,112,113].

5.2. Operational issues

Making the transformation from static to adaptive buildings is not only more demanding for the design process, it also adds an extra layer of complexity to the building's operation phase. Moloney [114] argues that application of CABS asks for the design of a process rather than an artefact. This is because the mere addition of adaptive features to the building envelope does not directly guarantee successful operation. The adaptive behavior of CABS simultaneously has to satisfy multiple, interdependent performance requirements, which are often competitive, and sometimes even conflicting in nature. Concerted activities are thus needed: the various subsystems in the façade have to cooperate, together and with other building services, to resolve conflicts, handle trade-offs, and preferably even work in symbiosis. The following trade-off options are representative for the many dimensions in control of CABS: daylight vs. glare, views vs. privacy, fresh air vs. draught risk, solar shading vs. artificial lighting, passive solar gains vs. potential overheating. Operation is further complicated under the influence of time-dependent effects. When dynamics play a role, delaying a decision might be better than an instant action, and also temporarily allowing a slight penalty in performance may be surpassed by benefits on the long run.

It can be concluded that operating CABS is not straightforward, leading to the assumption that traditional rule based control strategies will likely be inappropriate. There is a need for advanced supervisory control strategies that are able to evaluate several competitive alternatives to make well-informed decisions. Promising developments in this regard are formed by optimal control [115,116] and model based predictive control strategies supplied with weather forecasts [117,118].

5.3. Human aspects

At least as relevant as the energy saving argument of CABS is the potential for enhancing comfort conditions. Although the importance of considering human factors in design and operation of active building technologies is now widely recognized [119], there is still a lack of knowledge in this interdisciplinary research area [120]. Consensus has been reached that automated systems should provide conditions that satisfy the average person, while at the same time keeping options open to meet personal preferences [121]. To exploit human intelligence in control of CABS, occupants should be given some opportunity for adjustment or manual override [122]. The inability to overrule the system's decisions is the most frequently encountered complaint with intelligent building envelopes [123]. Stevens [124] even reports some cases of sabotage, where the occupants willfully tried to beat the behavior of active façades. A good way to avoid counterproductive operation is by paying special attention to usability of user interfaces and integration of feedback mechanisms in the control loop [125].

One of the open research questions associated with CABS and human factors pertains to the transient effects of 'switching'. Although the exact relationships are not yet quantified, it is believed that there exists a negative correlation between switching frequency and users' acceptation [126]. A possible solution is to constrain the rate of change to a certain maximum, notwithstanding the fact that in some cases instantaneous action is absolutely necessary.

5.4. Future perspectives

The enabling technologies for CABS concepts form an integral part of important technology roadmaps such as the Building Envelope and Window Research and Development Program from the United States Department of Energy [127] and IEA's Energy Technology Perspectives [128]. Findings from the present paper show that the field of CABS is indeed growing. In order to make effective contributions, it is essential that the emerging techniques can be deployed on a wide scale with competitive cost–benefit ratios. The majority of occupied buildings with CABS, however, were developed as bespoke solutions for individual projects. Although such concepts are important as a precedent for further developments, their actual contributions to a more sustainable built environment are limited. To realize the cumulative effects of deploying CABS on a regular basis, large-scale production of adaptable materials and components will be needed in the near future. This will require continued cross-disciplinary product

development efforts to bring more concepts to the market. Considering the promising number of prototype-phase technologies in Table 2, we foresee a growth in this direction.

Among the unpublished built examples with CABS [24], there seems to be a tendency for façades with dynamic exterior shading systems, sometimes enhanced with insulating properties. As these CABS concepts tend to be applied not only in high-profile, high-budget projects, it presents as a cost-effective solution that can bring distinct aesthetic quality to the building [20,114]. Such multi-functional shading systems fit in well with current construction practices, and are therefore attractive for facilitating a smooth transition towards widespread application of more advanced CABS concepts.

Considering the physical domains as defined in Table 1, there is a strong coupling between the thermal and optical domains. With daily and monthly fluctuating components, solar radiation is an environmental factor with high variability and direct consequences for thermal and visual comfort. Successful CABS should have the ability to act in response to fluctuations in solar radiation to ensure outside views while preventing glare discomfort and maintaining energy efficient building operation. In this respect, CABS with extrinsic control are most effective because they allow for advanced automated operation strategies and personal control. Although it would be relevant to assess the potential of long-term (e.g. seasonal) CABS in more detail, we expect short-term adaptive actions to be a more rewarding future direction. One of the promising technology options that fulfills these requirements are switchable windows. A further advantage of switchable glazing is that the technology is suitable for retrofit projects, where not only the relative impact, but also the potential number of projects is high. These beliefs are reflected in recent market forecast and analysis reports which predict a rapid growth of the market for switchable window technologies [129–131].

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